Understanding and Conscious Experience

Philosophical and Scientific Perspectives

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Chapter 1

Understanding in science and beyond

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1 Understanding in science and beyond

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1.1 Introduction

Scientific research can be pursued for a variety of aims, from purely intellectual aims to very practical ones. But, as W.V.O. Quine wrote in *The Pursuit of Truth* (1992, p. 20), "nowadays the overwhelming purposes of the science game are technology and understanding". That the pursuit of understanding is the central intellectual aim of science was also observed by physicist Erwin Schrödinger. In 1948 he gave a series of lectures in Dublin, which were later published in his book *Nature and the Greeks*. In this book he discusses how modern science was invented in ancient Greece, and asks: "What are the peculiar, special traits of our scientific world-picture?" Schrödinger answers this question as follows: "About one of these fundamental features there can be no doubt. It is the hypothesis that the display of Nature can be understood" (Schrödinger 1996, p. 90).

Scientists want to *understand* the world, and they appear to be quite successful in this respect. Physicists, for example, have achieved a profound understanding of phenomena both at the largest and at the smallest possible scales of nature. With Einstein's general theory of relativity, large-scale gravitational phenomena in the universe, such as gravitational lensing and black holes, are understood. The latest success of the theory was the detection of gravitational waves, in 2015. On the smallest scale, a recent success was the experimental discovery of the Higgs boson, which confirmed the theoretical hypothesis of the Higgs mechanism, providing an understanding of why elementary particles have mass. Understanding the world around us appears to be a central aim of science. But what precisely *is* scientific understanding, and how can it be achieved? In my previous work (De Regt 2017) I have developed a philosophical theory of scientific understanding that accounts for the plurality of ways in which understanding is achieved in scientific practice. The present chapter defends and extends this theory.

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The outline of the chapter is as follows. Section 1.2 presents a systematic analysis of the nature of understanding, and its relation to knowledge. This analysis supports my contextual theory of scientific understanding, which emphasizes the role of skills in understanding. In Section 1.3, this theory is illustrated with an example from the history of quantum physics. The remaining part of the chapter is concerned with the question of how understanding by experts relates to understanding by laypeople. Section 1.4 discusses how laypeople can acquire intuitive understanding in a particular domain, comparing scientific understanding with musical understanding. Section 1.5 analyzes the relation between expertise and understanding, and examines the prospects for public understanding of science.

1.2 Scientific understanding: What it is, and what it is not

Philosophers who have addressed the issue of understanding have traditionally related it to the activity of explanation: scientists try to explain the phenomena they observe, and when they have found a satisfactory explanation, the phenomenon is understood. Thus, understanding appears to be the product of scientific explanation. While the nature of scientific explanation has been debated extensively in the philosophy of science, until recently much less attention has been given to the understanding that results from such explanations. The views on understanding that have been offered can roughly be divided into two categories. I will discuss these in turn and show that both are misguided.

The first view assumes that understanding is nothing but a *subjective feeling*. Accordingly, it is perhaps of interest to psychologists but not to philosophers, because they typically focus on the objective features of science. Think, for example, of Archimedes, who had his famous “Eureka-experience” when he was taking a bath. Suddenly, he understood how he could find out whether or not the king’s crown was made of pure gold, with the help of the principle of upward buoyant force that was later named after him. Legend has it that he was so excited about this that he jumped out of his bath and ran around naked through the streets of Syracuse, shouting: *Eureka!* A good scientific explanation can indeed bring about such an ecstatic feeling of understanding, but it surely doesn’t happen every time. And what is more, it can also happen that a *bad* (incorrect) explanation causes a similar feeling of understanding. I suppose that most people know this from their own experience, at least I do: you think you understand why something has happened, but later it turns out that there is a completely different explanation for it. The feeling of understanding doesn’t distinguish between these cases, and it can accordingly be misleading. Some philosophers conclude from this that *explanation* is a respectable topic for the philosophy of science, but *understanding* is not (e.g., Trout 2002).

I agree that we should not attach too much value to the subjective feelings that can come with (good and bad) explanations. But this does not imply that the notion of "understanding" can be completely ignored by philosophers of science. When we look at the history of science, one notices that understanding is not just a superfluous by-product of explanations. This can be seen, for example, in the early history of quantum mechanics. The first quantum theory of atomic structure was published by Niels Bohr in 1913, and in the years that followed physicists tried to develop a more generally applicable quantum mechanics. In 1926 two candidates for such a general quantum mechanics appeared on the scene: the theory of matrix mechanics, proposed by Werner Heisenberg, and the theory of wave mechanics, developed by Erwin Schrödinger. This led to a heated debate about which of these theories was superior. Questions of which theory provided more understanding, and which theory was more intelligible, played a central part in the discussion.

The debate provoked strong emotions on both sides. Schrödinger wrote that he was "discouraged, if not repelled" by Heisenberg's theory because of its unintelligibility, while Heisenberg told his colleague and friend Wolfgang Pauli that he found Schrödinger's theory "appalling" and added: "What Schrödinger writes about intelligibility makes scarcely any sense. In other words, I think it is crap".[1] It may seem, at first sight, that this exchange is guided by subjective feelings. But, as I will explain below, the discussions between Schrödinger, Heisenberg and others about the way in which atomic structure can and should be understood were crucial for the development of quantum mechanics. So understanding is more than just a subjective feeling.

On a second, completely opposite view of understanding, the understanding that is produced by scientific explanations is a specific kind of objective knowledge, for example, knowledge of the causes of phenomena. Thus, Peter Lipton (2009, 30) writes: "Understanding is not some sort of super-knowledge, but simply more knowledge: knowledge of causes". For example, we know that since 1900 the average temperature on Earth has increased; we have objective knowledge of global warming. When climate scientists explain this phenomenon, by pointing at the so-called greenhouse effect and the increase of CO_2 in the atmosphere, they have added more objective knowledge, namely knowledge of the *cause* of global warming. This understanding-as-knowledge view, which is also defended by Strevens (2008) and Khalifa (2017), is implicit in many traditional approaches to epistemology and philosophy of science. To be sure, the view that understanding is a species of objective knowledge is more plausible than the idea that it is just a kind of subjective feeling. But also this view turns out to be problematic when it is examined in more detail. I will present three concrete objections to it.

A first problem is that "knowledge" presupposes truth: we can only *know* something if it is true. So, if "understanding of a phenomenon" is the same as "knowledge of the cause of a phenomenon", then we can only understand a phenomenon if we know the *true* cause of it. At first sight, this may seem quite reasonable. Consider, for example, the medieval theory about planetary motion, which assumes that the planets move because they are pushed by angels. This theory doesn't give us understanding, one might think, simply because it is not true. But while this seems a plausible argument, it turns out that not much understanding is left if we make truth a requirement for understanding. Another look at the history of science makes this clear almost immediately: many scientific theories from the past were quite successful at the *empirical* level: they could describe and predict a host of observable phenomena in their domain. But most of these theories were later rejected and were replaced with new theories that describe and predict the phenomena even better. These new theories are often in direct contradiction with the old ones, which means that they cannot both be true. So, despite their empirical success, the old theories turned out to be false after all. Does that mean that the scientists who developed and defended these theories lacked any understanding of the phenomena that they could describe and predict so well with their theories? I think that this conclusion does not do them justice.

An example is Newton's theory of gravitation. This theory was, and still is, extremely successful in describing and predicting gravitational phenomena, such as the motion of falling bodies on earth, ballistics, the tides and planetary motion. But from the viewpoint of currents physics, Newton's theory does not give us a true account of the cause of gravitational phenomena. Since 1919, when Arthur Eddington's observations of the bending of light by the sun confirmed Einstein's general theory of relativity, the latter theory is regarded as the true explanation of gravitation. Einstein's theory differs fundamentally from Newton's theory: according to Einstein, Newton's force of gravitation is a fiction: gravitational motion is caused by the curvature of space-time in the presence of masses. Does the fact that his theory turned out to be false imply that Newton did not have any understanding of gravitational phenomena? And that students in secondary school today, who still have to learn Newton's theory in their physics classes, do not acquire any understanding, but rather misunderstanding? I disagree: the case of Newton shows that also theories that we now know are false can still give us understanding, at least to some degree.[2]

A second problem for the view that understanding is a species of knowledge is that the history of science teaches us that criteria for understanding and intelligibility vary considerably in the course of time. In the seventeenth century, for example, the generally accepted view was that only a mechanics based on contact action is intelligible, while in the eighteenth century (as a result of the success of Newton's theory of gravitation) action-at-a-distance was regarded as the paradigm of intelligibility (see e.g., Van Lunteren 1991). Of course, one might claim that only one of these positions is the correct one, but that would not do justice to the history of science. A more plausible option is to acknowledge that understanding is *contextual*: criteria for understanding and intelligibility depend on the historical context (and also on the disciplinary context). The contextual nature of understanding appears incompatible with the idea that it is a species of objective knowledge.

A third problem for the idea of understanding as objective knowledge is that there appears to be an essential difference between understanding and knowledge. If you *know* what the cause of a particular phenomenon is, this does not imply that you *understand* that phenomenon. For example, merely knowing that global warming is caused by the increase of CO_2 in the atmosphere does not yet amount to understanding it. A student may be able to answer the question "Why does global warming happen?" correctly by answering "Because of the increase of CO_2 in the atmosphere". But this does not imply that she understands why global warming occurs – she merely knows what its cause is. This shows that understanding must be more than just having a particular type of knowledge. And this more, I submit, crucially involves *skills*. The student understands why global warming happens if she not only knows that it is caused by the increase of CO_2 but also "grasps" the causal, explanatory relation between cause and effect. In this case, she needs a theory or model of the climate system that includes the greenhouse effect. Moreover, she needs to be able to use that theory in order to derive the (causal) relation between the amount of CO_2 in the atmosphere and the mean global temperature. In sum, she has to have knowledge, but she also needs the *ability* to use her knowledge. The latter is the crucial skill-component of (scientific) understanding.[3]

The idea that understanding is an ability, a skill, is a central element of the contextual theory of scientific understanding that I have developed in De Regt (2017). My theory is based on an analysis of episodes from the history of science, which shows that criteria for what constitutes scientific understanding, and how to achieve it, change in the course of history. What is more, even at one and the same time scientists sometimes disagree about criteria for understanding. Such variation is possible because understanding is *context-dependent*. This is the case because understanding involves a thinking subject, an "understander". It is human beings who understand, and a human being is always part of a context – a historical and social context, for example. For scientists the context is in important ways determined by their disciplinary education, by their background knowledge and by the state-of-the-art in their field. So, whether or not a scientific theory can provide understanding is partly dependent on who the understanders are, and what their context is.

It might be objected that this makes understanding a purely subjective affair, that cannot be relevant to scientific explanation – which should be an objective and generally valid relation between a theory and the phenomenon to be explained. Although this is a plausible idea at first sight, it's not that simple. As Cartwright (1983) and Morgan and Morrison (1999) have shown, a closer look at scientific practice teaches us that the relation between abstract theories and concrete observable phenomena is usually not a direct one but one that is mediated by models. Reality is complex, and it is seldom the case that the behavior of a real system can be deduced directly from an abstract, general theory. The usual situation is one in which scientists first construe a simplified, idealized model of the system and then apply the theory to it. Constructing such models is an art – it is a matter of choosing the right idealizations and approximations. There are no strict rules or algorithms for building scientific models – it is a human activity that involves skills, which can only be acquired in practice.

So scientific explanation has a human face: scientists are humans who should be able to build suitable models to explain phenomena. Whether or not a scientist is able to construct a model that relates the theory with the phenomena depends on two factors: on the one hand, the *skills* of the scientist, and, on the other hand, the *qualities* of the theory. And there has to be a match between the two: scientists should have the right skills to work with the theory, to use it for building models of the phenomena. In other words, the theory has to be *intelligible* to them.

I conclude that scientific explanations of phenomena do give us understanding but that this requires that the theories used in the explanation are intelligible, where intelligibility is defined as *the value that scientists attribute to the cluster of qualities of the theory that facilitate its use*. Note that intelligibility, defined in this way, is not an intrinsic property of a theory but a context-dependent value, related to the skills of scientists. It does not make sense to say that the theory of evolution or quantum theory or the theory of the Higgs mechanism is intelligible, or unintelligible, in itself. Whether or not these theories are intelligible depends on the context in which they are used. It should be emphasized, though, that this context-relativity does not entail that understanding is subjective: there are still objective ways to test whether a theory is intelligible (to a scientist in a particular context).[4]

1.3 An example: Understanding the quantum world

I have introduced the notion of intelligibility and argued that this is a necessary condition for understanding the phenomena, understanding the world around us. Accordingly, the notions of intelligibility and understanding should be sharply distinguished, but there is also a relation between the two. Let me illustrate this with the case of quantum mechanics, a theory that is often regarded as unintelligible. Richard Feynman, one of the most brilliant physicists of the twentieth century, famously stated: "I think I can safely say that nobody understands quantum mechanics" (Feynman 1965, p. 129). It's unlikely that Feynman meant to say that physicists do not understand the *theory* of quantum mechanics, in the sense that they cannot work with it, that they cannot do the calculations. A more plausible interpretation of his statement can be gleaned from the famous *Feynman Lectures on Physics*, where he writes about the behavior of atoms: "Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects" (Feynman, Leighton, and Sands 1965, 1–1). In other words, even those who are well-versed in the theory of quantum mechanics have difficulty understanding a reality that behaves according to the laws of that theory. Feynman suggests that this has to do with the counter-intuitive nature of quantum theory. One example is the notorious wave-particle duality of light and matter, which makes an unambiguous visualization of electrons and photons impossible.

It was this kind of unintelligibility that played an important role in physics in the 1920s, when Heisenberg, Schrödinger and others struggled to develop a new foundation for quantum theory. Heisenberg's theory, matrix mechanics, used a type of mathematics that was difficult and not well-known at the time. Moreover, matrix mechanics was abstract: it was designed to predict observable phenomena, such as the frequency and intensity of spectral light that was emitted by atoms, but it did not give any concrete description of their inner structure. By contrast, the rival theory of Schrödinger, wave mechanics, *did* promise a concrete, visual model of atomic structure: it described atoms as a complex system of waves. Schrödinger's theory was also mathematically simpler than Heisenberg's matrix mechanics, because physicists were quite familiar with wave equations. In the mid-1920s supporters of the two theories were in fierce competition, and in the debate about the merits of the theories the notions of understanding and intelligibility played a central role.

Schrödinger argued that a physical theory has to be visualizable: only theories that offer a visual image of reality can give us an understanding of the phenomena. According to Schrödinger, visualizability is a necessary condition for scientific understanding, because "we cannot really alter our manner of thinking in space and time, and what we cannot comprehend within it we cannot understand at all" (Schrödinger 1984, p. 118, my translation). He argued that since wave mechanics promised a visualization of atomic structure, it was superior to matrix mechanics: only with wave mechanics can understanding of the phenomena be achieved. (Here it should be noted that Schrödinger used the term *Anschaulichkeit*, which has both a literal and a metaphorical meaning: visualizability and intelligibility.) As an additional argument in favor of wave mechanics, Schrödinger suggested that visualizable theories are more fruitful: solving problems and applying the theory to new situations is easier with a concrete picture in mind than with just an abstract mathematical theory. And this turned out to be true: Schrödinger's theory became far more popular than Heisenberg's theory, because it was easier to apply and to use for the construction of models of concrete physical systems. In other words, it was – at least in the mid-1920s – more intelligible, in my sense of the term.

The proponents of matrix mechanics tried to counter Schrödinger's arguments by claiming that understanding can also be reached without visualization. Heisenberg's friend and colleague Wolfgang Pauli, in particular, fiercely attacked Schrödinger's position. Already before Schrödinger published his theory, Pauli had criticized attempts to visualize atomic structure. In 1924, he wrote a letter to Niels Bohr, in which he compared physicists who tried to visualize atoms to small children who like picture books. He added:

> Even though the demand of these children for *Anschaulichkeit* is partly a legitimate and a healthy one, still it should never count as an argument for the retention of fixed conceptual systems. Once the new conceptual systems are settled, then also these will be *anschaulich*.
>
> (Pauli 1979, p. 188)

Thus, Pauli suggested that matrix mechanics is perhaps difficult to understand at first – it appears unintelligible – but that this may change in the future: once we are used to the new theory, once we are familiar with it, we will find it intelligible even if we cannot associate concrete, visual pictures with it. When that has happened, the theory will be *anschaulich*, not in the specific sense of "visualizable", but in the more general sense of "intelligible". In the late 1920s, these discussions about visualizability and intelligibility led to a synthesis of the two rival theories: a quantum mechanics that combined matrix mechanics and wave mechanics into a very successful theory of atomic structure, that still hasn't been superseded. Hence this historical episode illustrates how debates about understanding and intelligibility can stimulate scientific progress.

It also shows that a theory that allows for visualization is, for many scientists, easier to use than an abstract theory. Indeed, visualization remained an important tool for understanding, also in quantum physics, even though quantum particles are strictly speaking not visualizable. An example is the discovery of electron spin, by Samuel Goudsmit and Georg Uhlenbeck, who had difficulty understanding Pauli's abstract account of the properties of the electron in terms of quantum numbers. Using visual imagination they developed the idea of spin. Looking back on his discovery, Uhlenbeck wrote:

> [In Pauli's paper] four quantum numbers were ascribed to the electron. This was done rather formally; no concrete picture was connected with it. To us, this was a mystery. [...] We could understand it only if the electron was assumed to be a small sphere that could rotate.
>
> (Uhlenbeck quoted in van der Waerden 1960, p. 213)

Today, the concrete picture of rotation is still a useful guide for understanding, in physics education and in scientific research. But this does not entail that visualizability is a necessary condition for intelligibility. It is a quality of theories that is valued by scientists in particular contexts, because it facilitates the use of those theories. It is equally well possible, however, that some scientists – in some contexts – find abstract theories more intelligible; this was the case for Pauli and Heisenberg. This contextual variation is characteristic of scientific understanding.

1.4 Intuitive understanding in science and music

I have argued that scientific understanding can be achieved only if the skills of scientists accord with the qualities of the theories they use, to build models and construct explanations. This requires that scientists are in some sense familiar with the theory, that they have developed what may be called "intuitive insight" into the theory and its implications. Such insight shows, for example, when scientists can recognize qualitative consequences of the theory, without doing exact calculations. The relevant intuitions can be developed: scientists learn the skills to work with new theories during their university education and in scientific practice. Usually this is a gradual process, but in some situations – like in the case of quantum mechanics – radically new intuitions have to be developed, and this may require more effort. Think of Feynman's observation that also experts have difficulty understanding the quantum world, since it is so different from the everyday reality that has formed our intuitions.

Yet it does not seem to be impossible to develop new intuitions that guide us in the quantum domain. An ongoing citizen-science research project at Aarhus University suggests that even humans without any theoretical knowledge of quantum theory can contribute to solving problems in an environment governed by the laws of quantum mechanics. The researchers have developed an online computer game, *Quantum Moves 2*, in which players enter a virtual world where the laws of quantum theory hold.[5] The project is based on crowdsourcing: the game is freely accessible online, and everyone can participate without any training. Players contribute to solving problems such as the control and optimization of the production of Bose-Einstein condensates (Heck et al. 2018) and other optimization problems in the quantum domain (Jensen et al. 2021). Although the results are still tentative, they suggest that non-expert players can develop heuristics and intuitions that outperform randomly seeded numerical strategies and that may therefore be used as input for expert optimization strategies. These results are in line with my analysis of scientific understanding: intuitions are important, and they can be trained and developed.[6] Such intuitive understanding is partly a question of familiarization. But it is not just passive familiarization that occurs after-the-fact: understanding has an active role in scientific research.

The thesis that one may come to understand something when one becomes familiar with it does not sound implausible. Also in domains outside science, does this seem to be the case, for example, in music. When and how do we understand music? This has been a topic of discussion in the philosophy of music, and it appears that a comparison between scientific understanding and musical understanding highlights interesting features of both.[7] Most people (in Western society, or in the globalized modern world), even those who do not like classical music, will upon hearing a Mozart string quartet, feel that they understand this music in some way – it will not come across as totally unintelligible. When hearing a string quartet by twentieth-century composer Arnold Schoenberg, however, many people will react differently. Schoenberg broke with traditional musical rules and conventions in a radical way, and introduced a new method of composition: the 12-tone technique. Most listeners who hear Schoenberg's music for the first time will have some difficulty with it, and may perhaps think that they don't understand it.[8] A first response might be to think that understanding Schoenberg's music requires knowledge of his 12-tone system and the rules according to which his music is composed. This would imply that his music can be understood only by experts, by musicologists who have sufficient knowledge of music theory. But if that would be the case, there is no reason why this would not also hold for the music of Mozart. Why can ordinary listeners and music lovers, without much theoretical knowledge, still have the feeling that they understand the music of Mozart? Is this only a matter of being familiar with it?

The basic question is what it means to understand a piece of music. In his essay "Why is Schoenberg's music so difficult to understand?", composer Alban Berg, a pupil of Schoenberg, characterized musical understanding as follows: "to follow a piece of music as one follows the words of a poem in a language that one has mastered through and through means the same – for one who possesses the gift of thinking musically – as understanding the work itself" (Berg 1924, p. 184). After having analyzed one of Schoenberg's string quartets, Berg writes:

> We should not be surprised if an ear accustomed to the music of the last [nineteenth – HdR] century cannot follow such occurrences as here. In that music homophony almost always prevails, themes are made from symmetric two- and four-measure units, and developments and elaborations are largely unthinkable without numerous mechanical repetitions and sequences. All of this demands a relative simplicity in harmony and rhythm. Decades of familiarity with such things make the listener of today quite incapable of understanding music of a different type.
>
> (Berg 1924, p. 192)

Thus, according to Berg, it is indeed the unfamiliarity with the language of Schoenberg's music that prevents listeners from understanding it. So familiarization is a necessary condition, but is it also a sufficient condition for understanding? Philosophers of music have written extensively about the question of what musical understanding consists in, and what is required for it. Most of them agree that there exist levels and/or degrees of musical understanding, and that also listeners without musicological expertise can acquire such understanding, at least at some level or to some degree.[9] Malcolm Budd, for example, argues that even without possessing the relevant musical concepts or terminology a listener can experience a musical work with full understanding:

> To experience music with musical understanding a listener must perceive various kinds of musical processes, structures and relationships. But to perceive phrases, cadences, harmonic progressions, for example, does not require the listener to conceptualise them in musical terms.
>
> (Tanner and Budd 1985, p. 247)

The defining characteristics of a piece of music in a particular style can be observed even if one is unable to articulate and conceptualize them. According to Budd, the only advantage that expert musicologists have over non-expert listeners is that the former can explain the reasons behind their musical experiences and preferences. In a similar vein, Michael Tanner distinguishes three levels of understanding music, where understanding at the first level does not require any theoretical knowledge at all (Tanner and Budd 1985, pp. 227–232).

These analyses suggest a parallel between, on the one hand, musical understanding of experts and non-experts, and, on the other hand, the understanding of quantum phenomena by expert scientists and citizen scientists discussed above. Understanding a particular piece of music has to do, in part, with recognizing its structure. An expert in musicology can analyze and describe this structure, but ordinary listeners without such expertise can still *observe* structure.[10] After having heard works by Mozart and other composers from the classical era, one will become familiar with the structure of this kind of music, and this will make it easier to understand new music that is composed in the same style. In this way, listeners can develop "intuitive insight" with respect to music in a particular style, and this intuition can be used actively in order to understand new, unknown pieces of music.

So, musical understanding can be the result of familiarization, but it's not *only* a question of becoming familiar. Tanner cites Mozart's famous "Dissonance Quartet" (KV 465) as an example: while the introduction of the first movement is difficult to understand from a musicological perspective, listeners may become familiar with after repeated listening and get a feeling of understanding it. But this is mere habituation, it doesn't amount to genuine musical understanding (Tanner and Budd 1985, pp. 221–222). Similarly, someone who listens many times to the same Schoenberg quartet, but never to other works in this style, may come to like this one piece and may feel that he understands it. But this does not yet amount to *genuine* musical understanding. Such understanding requires that he has developed intuitions about, for example, its musical structure, intuitions that he can also apply to new music that he hears for the first time. And such intuitions will be developed only by listening to many different works in the same style.

The understanding that music lovers without background knowledge in music theory can have is comparable to the intuitive understanding that players of the game *Quantum Moves* acquire. They get used to the laws of quantum mechanics by moving around in the virtual reality of the game, developing skills to solve new problems, just like listeners develop the skills to understand and appreciate new pieces of music.

1.5 Expertise and public understanding of science

In the previous section, I argued that laypeople can acquire an "intuitive" understanding of phenomena in unfamiliar domains, be it in nature or in music. Such intuitive understanding is fundamentally different from the expert understanding that scientists or musicologists possess. The latter kind of understanding may seem to be beyond the reach of laypeople, especially with respect to science: current scientific understanding is often so advanced that it appears to be accessible only to specialists in the field. Still, it is important that laypeople can acquire some degree of understanding of scientific research. In present-day knowledge societies expert scientists need to communicate their knowledge and understanding to a wider public of non-experts.

One reason is that the solution of complex societal problems often requires collaboration between scientists from different disciplines. In such interdisciplinary research, experts need to share their knowledge and understanding with scientists from other disciplines, who do not have the same skills and expertise. And, more importantly, in many cases not only scientists but also citizen stakeholders will have to be included in the debates about how to solve societal problems. In cases such as climate change or the Covid-19 pandemic, for example, every citizen is a stakeholder. To solve problems like this, it is necessary that experts from different disciplines and laypeople understand each other and that the relevant science is sufficiently accessible and intelligible to those who are not specialists. Another reason for making science intelligible to laypeople is that scientists should explain to the public why their work is valuable. Today, science is frequently contested, and the value of scientific research is not taken for granted anymore. To some, science is "just another opinion". Such views should of course be countered, not by an appeal to the authority of science but by showing how valuable science is. And this implies that scientists should be able to communicate their results and make their work intelligible to the general public.

If my analysis of scientific understanding is correct, and if such understanding is dependent on specialist skills (e.g., advanced mathematical or experimental skills), then the question arises of how experts can communicate their understanding to an audience of non-experts, who do not have these skills. With this question, we enter the debate about "public understanding of science", which started in the mid-1980s. Initially, the attempts of scientists and science communicators to increase public understanding of science were guided by the so-called deficit model. This model assumes that the general public suffers from a knowledge deficit regarding science and that this can simply be resolved by enhancing public interest in and knowledge of science. The deficit model corresponds with an understanding-as-knowledge view: the general public has a scientific knowledge deficit, which should be eliminated by science communication. Unfortunately, the deficit model does not appear to work. This is clear, for example, from the failure to convert citizens opposing vaccination or cellular telephone networks. Critics of the deficit model argue that the reason for this is that the model is based on one-way communication from expert to layperson, in which no attention is paid to the context of the receivers, for example to their background, interests and values (Lewenstein and Brossard 2006).

Another reason for the failure of the deficit model may be that it assumes that understanding of science is simply knowledge of scientific facts. I have argued (in Section 1.2) that this is a mistake: understanding is more than just knowledge – it also involves skills. However, this might seem to entail that laypeople can only obtain understanding of science if they acquire the same skills as the experts, which would make them experts as well. This is obviously impossible: if one needs highly specialized mathematical or experimental skills for genuine understanding of science, then such understanding will be inaccessible to the wider public. Thus, expert understanding and public understanding of science are different, but is this a difference in kind or merely in degree?

To answer this question, we may benefit from work by sociologists of science Harry Collins and Robert Evans on the nature of scientific expertise. Based on fieldwork, they have developed a theory of expertise and compiled a “periodic table of expertise” (Collins and Evans 2007, p. 14; Collins 2014, p. 62). A basic tenet of their theory is that expertise involves skills (tacit knowledge) acquired through interaction with others who already possess the expertise in question. Among the various types of expertise that Collins and Evans distinguish, the most significant and well-supported ones are “contributory expertise” and “interactional expertise”. Contributory expertise is the expertise of those specialists who contribute to an area of expertise, for example, by developing new theories or making new discoveries. According to Collins (2014, p. 65), one becomes a contributory expert by “working with other contributory experts and picking up their skills and techniques – their tacit knowledge of how to do things”. These experts are the true specialists in a field. Note that this entails that even within science most people are contributory experts only in a very restricted domain.

When scientists communicate with colleagues in different areas of expertise, they rely on what Collins and Evans (2007, p. 28) call interactional expertise: “expertise in the *language* of a specialism in the absence of expertise in its *practice*”. People who possess interactional expertise but no contributory expertise can fluently communicate and interact with the contributory experts in a field, although they cannot do research themselves. Like contributory expertise, interactional expertise involves tacit knowledge and is accordingly acquired in a similar way, namely “by engaging in the spoken discourse of an expert community to the point of fluency but without participating in the practical activities or deliberately contributing to those activities” (Collins 2014, p. 68). Interactional expertise is very important within science. Since most scientists are contributory experts only in a very small area of research, their interaction with experts from neighboring areas requires interactional expertise (think of interdisciplinary collaboration, peer-reviewing, and committee work with respect to research activities). But it is also quite difficult to acquire, especially for non-scientists: it takes many years of immersion in a community to become an interactional expert. For example, Collins' own interactional expertise with respect to gravitational wave research was acquired after spending 30 years in the community of physicists. It seems reasonable to say that those who have such interactional expertise also possess a high degree of understanding. They can have fruitful communication and interaction with experts in a specific research field, and while they can't *do* such research, they can *talk* about it on the same level as the experts. Someone with interactional expertise does not only have a lot of factual knowledge but also has the skills to use that knowledge, to reason with it and discuss it in a meaningful way.

Collins and Evans' account of expertise appears to be compatible with my contextual theory of scientific understanding, especially when it comes to contributory expertise. The intelligibility condition, which demands a match between scientists' skills and theoretical qualities, needs to be fulfilled for contributory experts who want to increase scientific understanding by constructing new models and explanations. But it is not only contributory experts who possess scientific understanding. As acquiring contributory expertise is a gradual process (Collins and Evans (2007, pp. 24–25), also those who are on their way to becoming experts (e.g., university students) will already have some degree of understanding. Even when they cannot yet contribute to scientific research, they gradually develop the specialist skills needed to explain phenomena in their domain. The same holds for interactional expertise: acquiring such expertise is a gradual process as well, involving specialist skills (Collins and Evans 2007, pp. 33–34). While true interactional experts possess a high degree of scientific understanding, the process of acquiring interactional expertise involves a gradual increase of understanding. Hence, while there are different *kinds* of expertise regarding science, scientific understanding appears to be a matter of *degree*.

What does this imply for public understanding of science? Ideally, in order to communicate and interact fruitfully with scientific experts, interested laypeople (e.g., citizen stakeholders) should be full interactional experts. This is a very demanding requirement, however: to become an interactional expert, one has to be immersed in a community of contributing experts for a long time. Accordingly, full interactional expertise is extremely rare among laypeople (Collins 2014, pp. 73–74). But since there are degrees of understanding within interactional expertise, one may still consider it a regulative ideal. Interactional expertise requires specialist skills – not the technical, experimental or mathematical ones that contributory experts have – but the specific skills needed for understanding and discussing relevant scientific concepts, theories, etc.

In sum, genuine public understanding of science is more than just factual knowledge: like expert scientific understanding, it involves skills. The challenge for science communicators is to find ways to transfer these skills to the general public, at least to some degree. How can scientists and science journalists popularize scientific research in such a way that non-experts acquire these skills? An effective way to make abstract scientific concepts and theories intelligible to a wider public is to employ analogies or metaphors. Analogies and metaphors can increase understanding of an unfamiliar (e.g., abstract) domain by mapping it onto a more familiar (e.g., concrete) domain. By relating unfamiliar concepts to familiar ones, analogies and metaphors do not add new knowledge but enhance relevant conceptual reasoning abilities (Lakoff 1993). Interestingly, analogical and metaphorical reasoning is also used within science, and it turns out that the same metaphors can later be used to communicate scientific understanding to the general public (see Knudsen 2003).

A type of analogical reasoning that is widely used both in scientific research and in science communication involves visual metaphors. Richard Feynman, who was an absolute expert in quantum physics but also very good in communicating his knowledge and understanding to laypeople, is a famous example of a scientist who used visual thinking very effectively, both in his scientific work (cf. Feynman diagrams) and in his educational and popularizing work (Feynman, Leighton, and Sands 1965; Feynman 1965). Today, with digital tools and the internet, the possibilities for visual science communication have become almost unlimited. Good examples can be found on the YouTube channel Veritasium, by physicist Derek Muller, who explains difficult and abstract scientific topics in an entertaining and instructive way. In the clip in which he explains the notoriously counterintuitive concept of quantum entanglement, for instance, he makes effective use of various visual analogies. Not surprisingly, he also uses the same visual analogy that inspired the discoverers of electron spin in the 1920s (see Section 1.3). Another famous example of how (visual) analogies can help to make an abstract scientific concept intelligible is David Miller's now classic "cocktail party analogy" for the Higgs mechanism and the Higgs boson.[11] To be sure, such analogies can never be perfect, and metaphor use runs a risk of oversimplification leading to misunderstanding. However, if used in a well-considered and careful way, metaphors and analogies can convey at least some genuine understanding that provides laypeople with the skills to discuss science in a fruitful way.

1.6 Conclusion

The value of science is often considered to lie in the understanding that it produces. To arrive at such understanding expert scientists use the specialist skills they have acquired during their education and in professional practice. The contextual theory of scientific understanding that I have defended in this chapter offers a philosophical account of the nature of expert scientific understanding and the ways in which it is achieved in scientific practice. My analysis of scientific understanding in terms of specialist skills raises the question of whether, and if so to what extent, such understanding is accessible to non-experts as well. This is an important issue since many contemporary societal problems can only be solved when expert scientists collaborate with scientists from different disciplines and with citizen stakeholders. Such collaboration requires effective communication of the relevant science, in which scientific understanding is conveyed to non-experts.

I have addressed this question by analyzing the similarities and differences between expert understanding and understanding by laypeople. It turns out that both types of understanding involve skills (albeit different ones), which give rise to intuitions with respect to the phenomena in the relevant domain. Hence, enhancing "public understanding of science" is not simply a matter of knowledge transfer: it also requires that laypeople acquire the skills to use this knowledge, to reason with it, and to have meaningful discussions about science. One way to achieve this is by using analogies and metaphors in science communication.

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Notes

1 See below for the full quotations and sources.

2 See De Regt (2015) for a more detailed argument.

3 A more sophisticated variant of the understanding-as-knowledge view might claim that understanding is knowledge of an explanation. Thus, what would be required is not merely knowledge that the greenhouse effect causes global warming but knowledge that the greenhouse effect (causally) explains global warming. Whether this is a satisfactory response depends on how "knowledge of an explanation" is defined (cf. the "simple view" defended by Strevens 2008). I submit, however, that this move doesn't solve the problem, unless the definition of "knowledge of an explanation" includes skills.

4 One such test is based on the criterion that a scientific theory is intelligible for scientists (in a particular context) if they can recognize qualitatively characteristic consequences of it without performing exact calculations (De Regt 2017, pp. 101–108).

5 See https://www.scienceathome.org/.

6 Research in psychology supports the thesis that intuitions play a role in reasoning and decision making. See, for example, Gigerenzer (2007) and Kahneman (2011). Gigerenzer argues that intuitions are produced by heuristics that have been developed in evolutionary processes of adaptation. Kahneman emphasizes that intuitions can also lead us astray.

7 Scientific understanding and musical understanding obviously also differ in important respects. For example, according to Roger Scruton, in contrast to scientific understanding, musical understanding is a form of intentional understanding (Tanner and Budd 1985, p. 239).

8 Excepting Schoenberg's early works, which were still written in a Late Romantic style.

9 Among them are Tanner and Budd (1985), Levinson (1997), and Davies (2011).

10 According to Levinson (1997, pp. 13–14), non-expert listeners can acquire full musical understanding, which does not even require a grasp of structure: it is "a matter of apprehending individual bits of music and immediate progressions from bit to bit". But this view is far from generally accepted; see Kivy (2001, pp. 183–217) for a critical reply.

11 For an explanation plus video clip, see https://www.symmetrymagazine.org/article/september-2013/famous-higgs-analogy-illustrated.

References

Berg, A. (1924/2014). "Why is Schönberg's music so difficult to understand?" In: W. Reich, *The Life and Work of Alban Berg* (pp. 189–204). London: Thames & Hudson. Reprinted in B. R. Simms (ed.), *Pro Mundo-Pro Domo: The Writings of Alban Berg* (pp. 183–195). Oxford: Oxford University Press.

Cartwright, N. (1983). *How the Laws of Physics Lie*. Oxford: Clarendon.

Collins, H. (2014). *Are We All Scientific Experts Now?* Cambridge: Polity Press.

Collins, H. & Evans, R. (2007). *Rethinking Expertise*. Chicago: University of Chicago Press.

Davies, S. (2011). *Musical Understandings and Other Essays on the Philosophy of Music*. New York: Oxford University Press.

De Regt, H. W. (2015). "Scientific understanding: truth or dare?" *Synthese* 192 (12): 3781–3797.

De Regt, H. W. (2017). *Understanding Scientific Understanding*. New York: Oxford University Press.

Feynman, R. P. (1965). *The Character of Physical Law*. Cambridge, Mass.: MIT Press.

Feynman, R. P., Leighton, R. B., and Sands, M. (1965). *The Feynman Lectures on Physics, Volume III*. Reading, MA: Addison-Wesley.

Gigerenzer, G. (2007). *Gut Feelings. The Intelligence of the Unconscious*. London: Penguin Books.

Heck, R., et al. (2018). "Remote optimization of an ultracold atoms experiment by experts and citizen scientists". *Proceedings of the National Academy of Sciences* 115 (48): E11231–E11237.

Jensen, J. H. M., et al. (2021). "Crowdsourcing human common sense for quantum control". *Physical Review Research* 3, 013057.

Kahneman, D. (2011). *Thinking, Fast and Slow*. London: Allen Lane.

Khalifa, K. (2017). *Understanding, Explanation, and Scientific Knowledge*. Cambridge: Cambridge University Press.

Kivy, P. (2001). *New Essays on Musical Understanding*. Oxford: Oxford University Press.

Knudsen, S. (2003). "Scientific metaphors going public". *Journal of Pragmatics* 35: 1247–1263.

Lakoff, G. (1993). "The contemporary theory of metaphor". In: A. Ortony (ed.), *Metaphor and Thought* (2nd edition, pp. 202–251). Cambridge: Cambridge University Press.

Levinson, J. (1997). *Music in the Moment*. Ithaca: Cornell University Press.

Lewenstein, B. V. & Brossard, D. (2006). "Assessing models of public understanding in ELSI outreach materials". Final Report, Cornell University.

Lipton, P. (2009). "Understanding without explanation." In: H.W. de Regt, S. Leonelli & K. Eigner (eds), *Scientific Understanding: Philosophical Perspectives* (pp. 43–63). Pittsburgh: University of Pittsburgh Press.

Morgan, M. & Morrison, M., eds. (1999). *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press.

Pauli, W. (1979). *Wissenschaftliche Briefwechsel, Band 1: 1919–1929*. A. Hermann, K. Von Meyenn & V. Weisskopf (eds.). New York: Wiley.

Quine, W. V. O. (1992). *The Pursuit of Truth*. Cambridge, Mass.: Harvard University Press.

Schrödinger, E. (1984). *Gesammelte Abhandlungen, Band 3*. Wien: Verlag der Österreichischen Akademie der Wissenschaften.

Schrödinger, E. (1996). *Nature and the Greeks*. Cambridge: Cambridge University Press.

Strevens, M. (2008). *Depth: An Account of Scientific Explanation*. Cambridge, Mass.: Harvard University Press.

Tanner, M. & Budd, M. (1985). "Understanding music". *Proceedings of the Aristotelian Society, Supplementary Volumes* 59: 215–248.

Trout, J. D. (2002). "Scientific explanation and the sense of understanding". *Philosophy of Science* 69: 212–233.

Van der Waerden, B. L. (1960). "Exclusion principle and spin". In: M. Fierz & V.F. Weisskopf (eds.), *Theoretical Physics in the Twentieth Century* (pp. 199–244). New York: Interscience Publishers.

Van Lunteren, F. (1991). *Framing Hypotheses*. Ph.D. Dissertation, University of Utrecht.